Charm physics in NA61/SHINE

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NA61/SHINE (SPS Heavy Ion and Neutrino Experiment) is a multi-purpose spectrometer optimised to study hadron production in different types of collisions: p+p, p+A, A+A.

More details: 26/04; 12:30, Andrey Seryakov "Results from the NA61/SHINE energy and system size scan program"

Overview

1. Motivation of open charm measurements
2. First measurements in NA61/SHINE
3. Precise open charm studies after Long Shutdown 2

Motivation of open charm measurements

Motivation of open charm measurements

Three main questions that motivate open charm measurements at the CERN SPS:

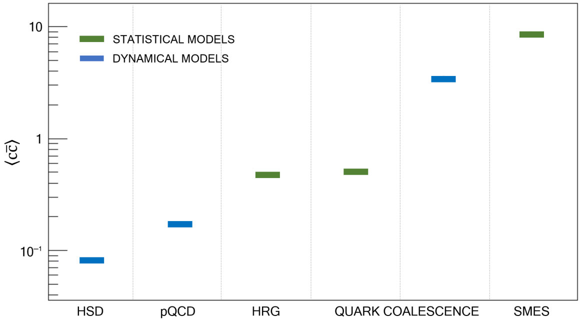
1. What is the mechanism of open charm production?
2. How does the onset of deconfinement impact open charm production?
3. How does the formation of quark-gluon plasma impact J/ψ production?

To answer these questions **mean number of charm quark pairs** $\langle c\bar{c}\rangle$ produced in the full phase space in A+A collisions has to be known.

Up to now corresponding experimental data **does not exist**.

Models of charm production

Predictions for $\langle c\bar{c}\rangle$ in central Pb+Pb collisions at beam momentum of 158A GeV/c differ by about **two orders of magnitude**.



HSD:
Linnyk, Bratkovskaya, Cassing, IJMP E17 1367.
pQCD:
Gavai *et al.* IJMP A 10 2999.
Braun-Munzinger, J. Stachel, PL B 490, 196.
HRG, Quark Coalesc. Stat.:
Gorenstein, Kostyuk, Stoecker, Greiner, PL B 509, 277.
Quark Coalesc. Dyn.:
Levai, Biro, Csizmadia, Csorgo, Zimanyi, JP G 27, 703.
SMES:
Gazdzicki, Gorenstein, APP B30, 2705.

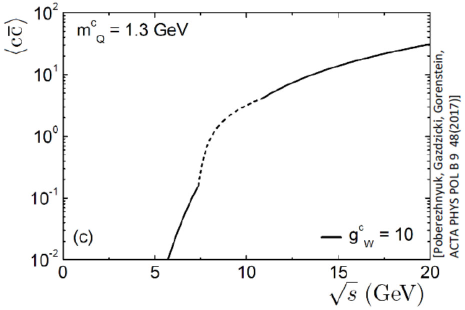
Charm yield as the signal of deconfinement

Phase Transition: $T_c \approx 150$ MeV

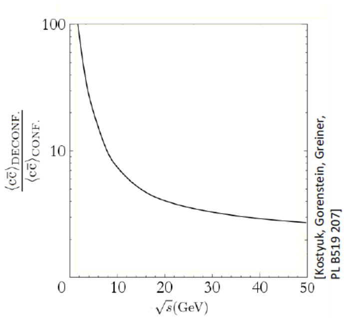
confined matter	$\longrightarrow$	quark-gluon plasma
$D\bar{D}$ mesons	$\longrightarrow$	(anti-)charm quarks
$2M \approx 3.7$ GeV	$\longrightarrow$	$2m \approx 2.6$ GeV

central Pb+Pb collisions

Statistical Model of Early Stage

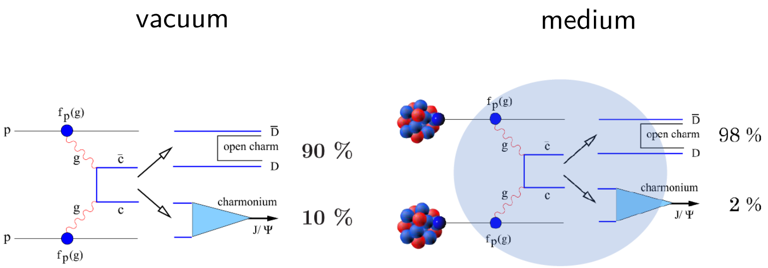


QCD-inspired calculations



J/ψ suppression as the signal of deconfinement

Open charm and J/ψ production within Matsui-Satz model [PL B178 416]



[Satz, Adv. High Energy Phys. 2013 (2013) 242918]

$$P(c\bar{c} \to J/\psi) \equiv \frac{\langle J/\psi \rangle}{\langle c\bar{c} \rangle} \equiv \frac{\sigma_{J/\psi}}{\sigma_{c\bar{c}}}$$

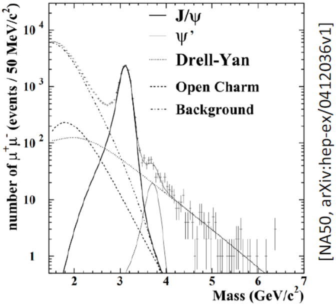
Medium reduces probability of J/ψ production.

J/ψ suppression as the signal of deconfinement

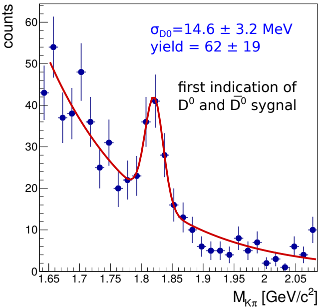
Calculation of $P(c\bar{c} \to J/\psi)$ requires data on:

- $\langle J/\psi \rangle$ - precise data at SPS by NA38, NA50, NA60
- $\langle c\bar{c} \rangle$ - can be estimated from open charm measurements started by NA61/SHINE

NA50



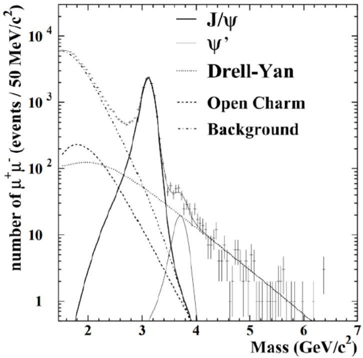
NA61



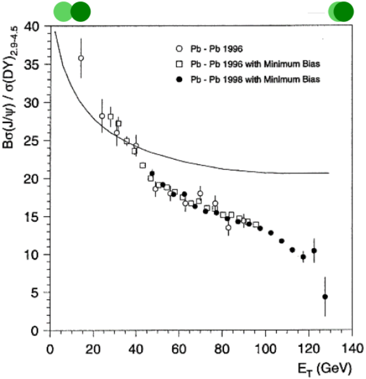
central Pb+Pb at 150-158A GeV/c

J/ψ production at CERN SPS

Data on J/ψ production has been normalized by the Drell-Yan yield



[NA50, arXiv:hep-ex/0412036v1]



[NA50, PL B 477 28–36]

Interpretation of these results is based on assumption:

$$\langle c\bar{c} \rangle \sim \langle DY \rangle$$

First measurements in NA61/SHINE

Open charm distribution

0-20% Pb+Pb at 158 GeV/c

charm conservation

c = $\bar{c}$

violation of izospin symetry

D^0 ($c\,\bar{u}$) 31% ≈ 2.6 D^+ ($c\,\bar{d}$) 12%

$\bar{D}^0$ ($\bar{c}\,u$) 31% ≈ 2.6 D^- ($\bar{c}\,d$) 12%

higher mass states

D_s^+ ($c\,\bar{s}$) 5% Λ_c (udc) 3% > D_s^- ($\bar{c}\,s$) 2% $\bar{\Lambda}_c$ ($\bar{u}\bar{d}\bar{c}$) 5%

$\langle n \rangle / \langle n_{ALL} \rangle$

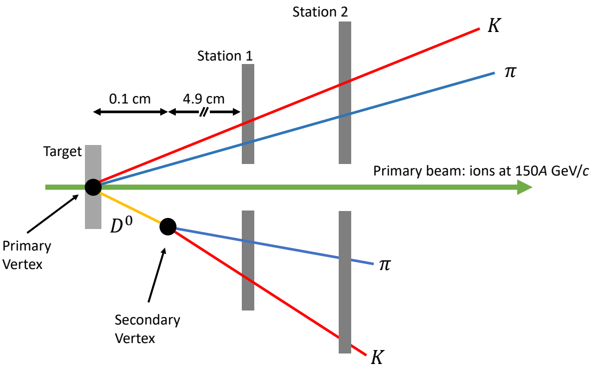
PHSD, Elena Bratkovskaya & Taesoo Song, private communication

What can NA61/SHINE measure?

- $D^0 \rightarrow \pi^+ + K^-$
  $c\bar{\tau} \approx 123\ \mu m$
  BR = 3.89%
- $D^+ \rightarrow \pi^+ + \pi^+ + K^-$
  $c\bar{\tau} \approx 312\ \mu m$
  BR = 9.22%
- $D_s^+ \rightarrow \pi^+ + K^+ + K^-$
  $c\bar{\tau} \approx 150\ \mu m$
  BR = 5.5%
- $\Lambda_c^+ \rightarrow p + \pi^+ + K^-$
  $c\bar{\tau} \approx 60\ \mu m$
  BR = 5.0%

Up to now only $\langle D^0 \rangle$ measurements were tested, but after Long Shutdown 2 at CERN (2019-2020) NA61/SHINE will be able to measure all of the most popular carriers of c and $\bar{c}$ quarks.

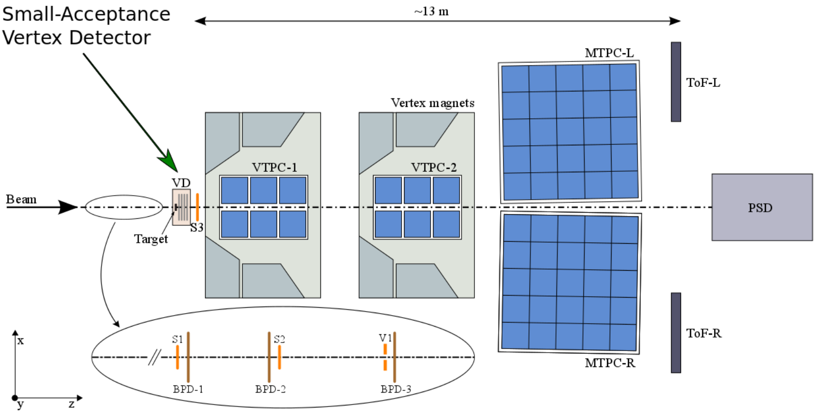
Open charm measurement concept



$D^0 \rightarrow \pi^+ + K^-$
$\bar{c\tau} \approx 123\ \mu m$
$\mathrm{BR} = 3.89\%$

Vertex Detector is needed to reconstruct primary vertex and secondary vertices with high precision.

NA61/SHINE detector



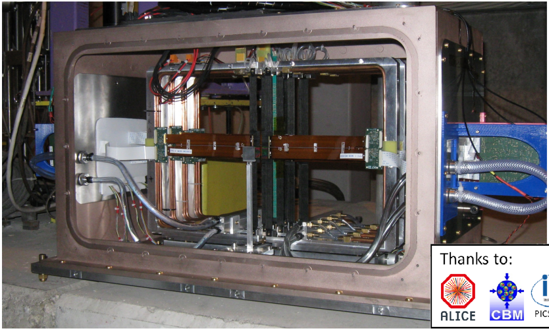
Small Acceptance Vertex Detector (SAVD)

Small Acceptance Vertex Detector introduced in 2016:

- 16 CMOS MIMOSA-26 sensors located on two horizontally movable arms
- target holder integrated

Achieved goals:

- tracking in large track multiplicity environment
- precise primary vertex reconstruction
- TPC-SAVD track matching
- first search of D^0 and $\bar{D}^0$ signal

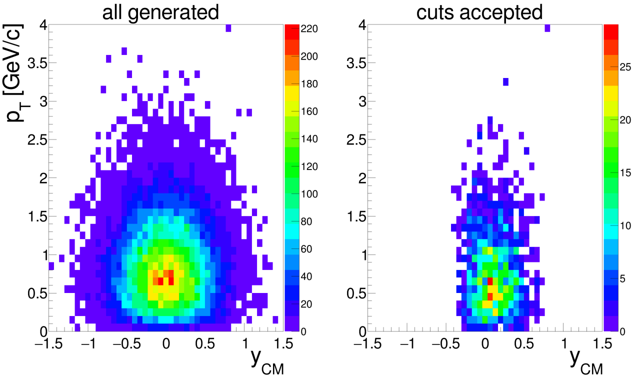


Thanks to:

ALICE CBM PICSEL Group TRB - collaboration

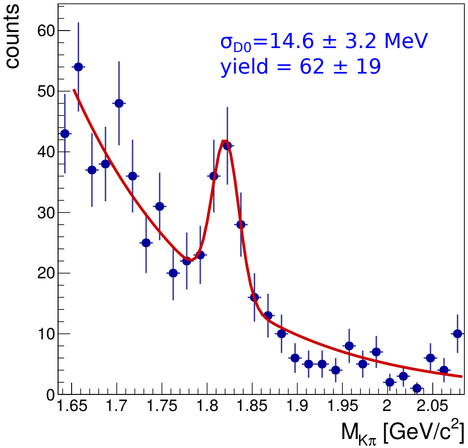
Acceptance of SAVD

AMPT simulations for central Pb+Pb collisions at 150A GeV/c
SAVD reconstructs 5% out of all $D^0 \to \pi^+ + K^-$ decays



Test data taking – December 2016
Pb+Pb at 150A GeV/c

First indication of D^0 and $\bar{D}^0$ peak

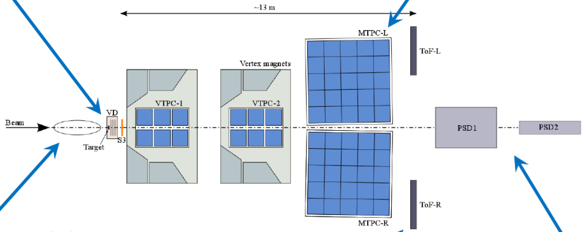


Precise open charm studies after Long Shutdown 2

NA61/SHINE upgrades

Construction of Vertex Detector (VD)
for D^0, $\overline{D^0}$ decay reconstruction

Replacement of the TPC
read-out electronics
to increase data rate to 1 kHz



New trigger and data
acquisition system

New Time-of-Flight
detectors

Upgrade of Projectile
Spectator Detector

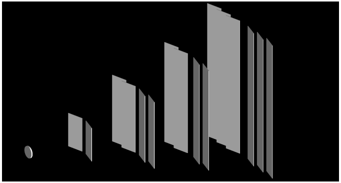
NA61/SHINE Vertex Detector

General requirements:

- precise vertex measurement
- fast detectors with high granularity
- low material budget
- large acceptance

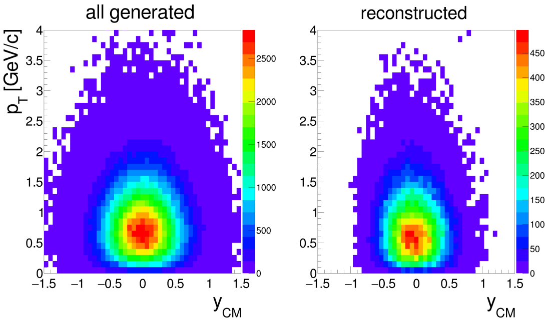
Technology developed for
ALICE ITS – ALPIDE sensors:

- very low noise
- fast readout
- two possible working modes:
  continuous and triggered readout



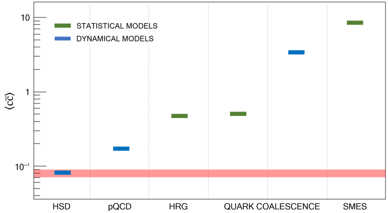
Acceptance of NA61/SHINE VD

AMPT simulations for central Pb+Pb collisions at 150A GeV/c
VD reconstructs 13% out of all $D^0 \rightarrow \pi^+ + K^-$ decays
Corrected results will refer to >90% of total open charm yield

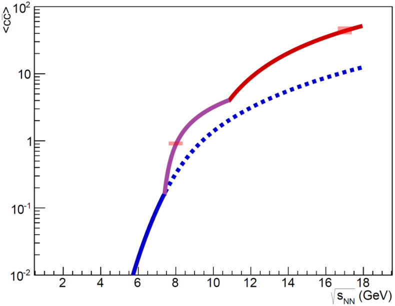


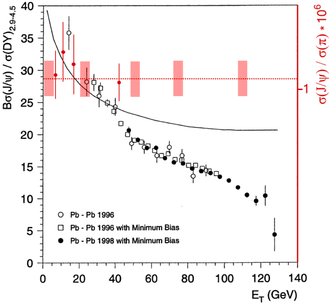
Total systematic uncertainty of $\langle D^0 \rangle$ and $\langle \bar{D}^0 \rangle$ is expected to be about 10%.

Impact of NA61/SHINE open charm measurements



accuracy of NA61 2020+ result





Summary

NA61/SHINE charm program addresses the following questions:

1. What is the mechanism of open charm production?
2. How does the onset of deconfinement impact open charm production?
3. How does the formation of quark-gluon plasma impact J/ψ production?

To answer these questions NA61/SHINE is planning to perform precise measurements of mean multiplicity of charm quark pairs after Long Shutdown 2.

Only NA61/SHINE can perform this measurement in the near future.

VD - team

- Kraków (Jagiellonian University):
  P. Staszel (Project coordinator), Y. Ali, D. Larsen, A. Merzlaya
- Kraków (AGH): M. Baszczyk, P. Dorosz, W. Kucewicz, Ł. Mik
- GU Frankfurt: M. Deveaux, M. Gaździcki, M. Koziel, A. Snoch
  Thanks to: P. Klaus, J. Michel, M. Wiebusch
- Warsaw: A. Aduszkiewicz, W. Bryliński, D. Tefelski
- St. Petersburg State University: G. Feofilov
- ETH Zürich: S. Di Luise

and many others...

PICSEL Group

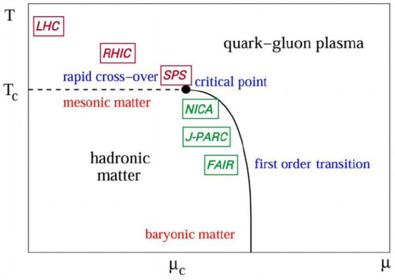
TRB - collaboration

Thank you!!!

Backup

Uniqueness of NA61 open charm program

Landscape of present and future heavy ion experiments

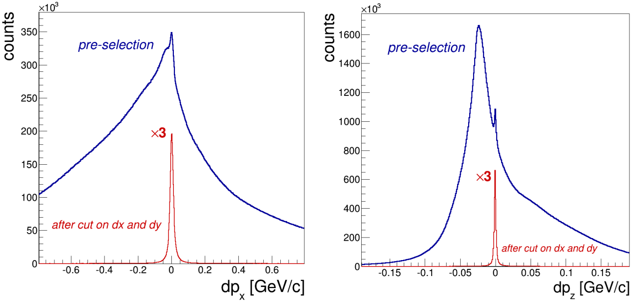


NA61/SHINE is the only experiment which is able to measure open charm production in heavy ion collisions in full phase space in the near future.

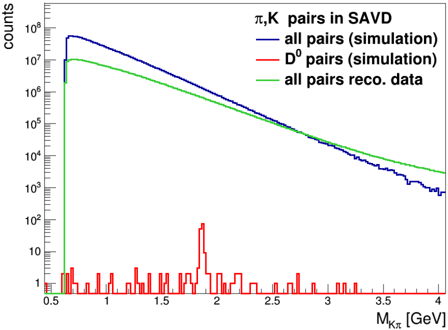
- LHC and RHIC at high energies: measurement in small phase space due to collider geometry and kinematics
- RHIC BES collider: measurement not possible due to collider geometry and kinematics
- RHIC BES fixed-target: measurement require dedicated setup – not under consideration
- NICA ($<80A$ GeV/c): measurement during stage 2 under consideration
- J-PARC ($<20A$ GeV/c): maybe possible after 2025
- FAIR ($<10A$ GeV/c): not possible

SAVD-TPC track matching

- extrapolate SAVD and TPC tracks to the common surface
- preselection: cut on y-slope of tracks
- After cut on dx and dy clear correlation peaks are visible in dpx and dpy distributions



Search for D^0 and $\bar{D}^0$

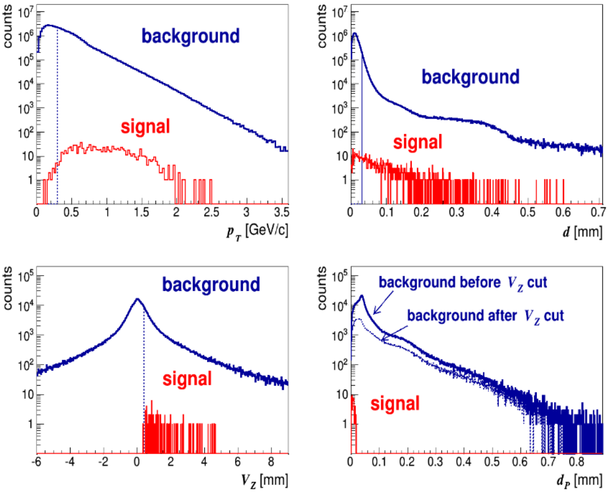


Combinatorial background is reduced by the cuts on:

- track transverse momentum
- track impact parameter
- longitudinal distance between primary and secondary vertices
- pair impact parameter

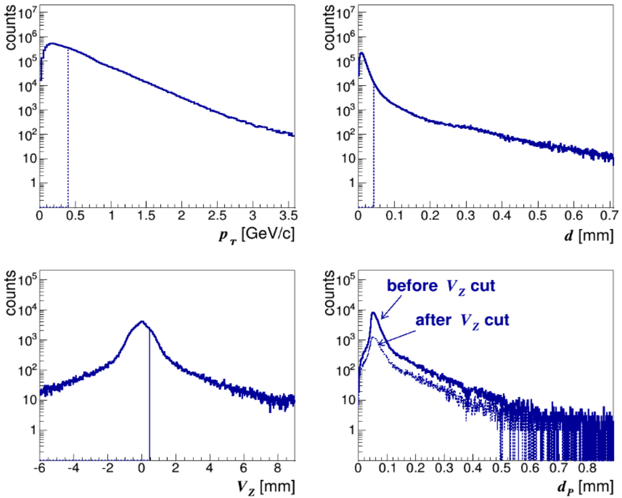
Cuts – simulations

simulation

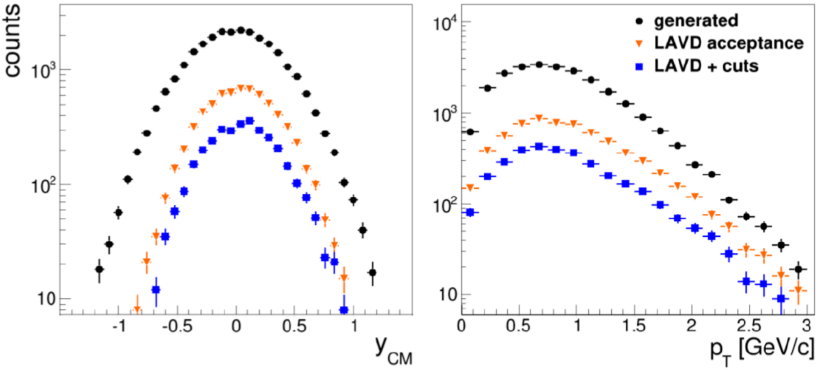


Cuts – data

data



LAVD acceptance



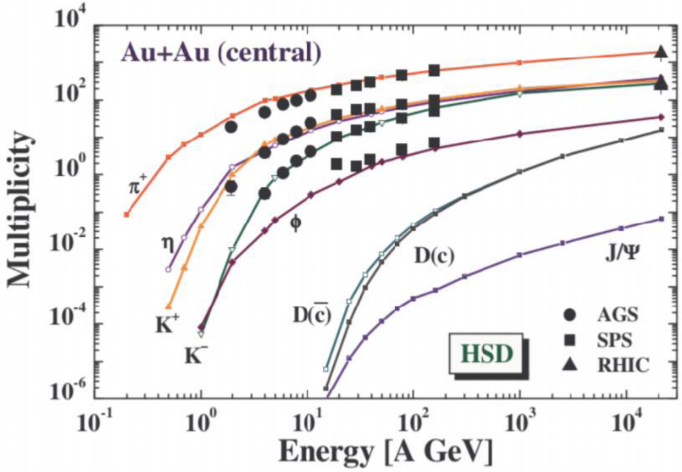
VD Efficiency

4% detection efficiency is calculated in respect to all D0s in that decayed to pi+K channel, so it includes:

- suppression due to two particle combined acceptance of SAVD and VTPC1+VTPC2.
- suppression due to matching efficiency between SAVD and VTPCs (98% in simulation)
- suppression due to background suppression cuts. These cuts suppress background by factor of 10^6 (in the D0 invariant mass region) and D0->pi+K by factor of about 2.

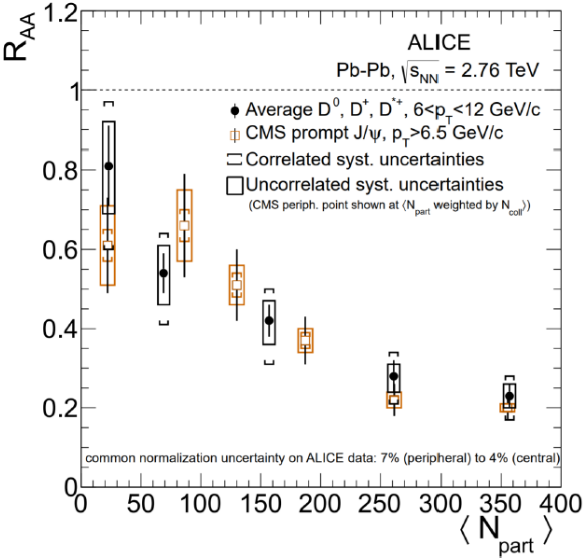
Full version has efficiency of 12% mostly due to increase of the combined LAVD + VTPC1+VTPC2 acceptance for D0->pi+K by factor of 3.

HSD predictions

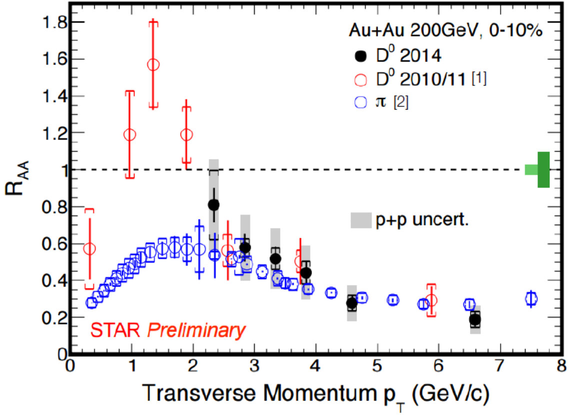


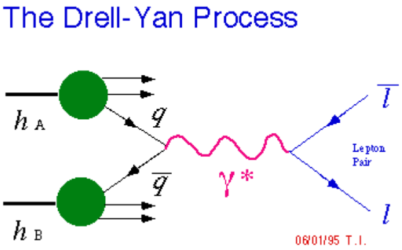
[Linnyk, Bratkovskaya, Cassing, IJMP E17 1367]

LHC charm measurements



RHIC charm measurements





- lepton pair production in hard EM interactions of two hadrons
- process not influenced by QGP production
- $\langle DY \rangle \sim N_{coll}$

Example of J/ψ normal nuclear absorption:
$J/\psi + h \rightarrow D + \bar{D} + X$
$J/\psi + \pi \rightarrow D + \bar{D}$

MIMOSA-26 sensors

- 1152x576 pixels of 18.4x18.4 μm^2
- readout time: 115.2 μs
- 50 μm thin
- SAVD: 16 sensors; 32 cm^2; 10 MPixel

Data taking

Data taking with Small Acceptance Vertex Detector before Long Shutdown 2:

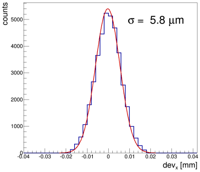
- December 2016 – test run for SAVD – Pb+Pb at 150A GeV/c
- November 2017 – Xe+La at 150A GeV/c and 75A GeV/c
- 2018 – pilot data taking – Pb+Pb at 150A GeV/c

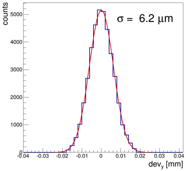
December 2016 – Pb+Pb at 150A GeV/c

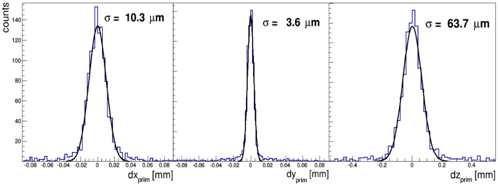
From the analysis of collected Pb+Pb data:

- Clusters spacial resolution: $\sigma_{x,y}(Cl) \approx 5\ \mu m$
- Primary Vertex resolution:
  $\sigma_x(PV) \approx 5\ \mu m$
  $\sigma_y(PV) \approx 1.8\ \mu m$
  $\sigma_z(PV) \approx 30\ \mu m$

$\sigma_x(PV) > \sigma_y(PV)$ due to magnetic field difference: $B_y > B_x \approx 0$







Vertex Detector software

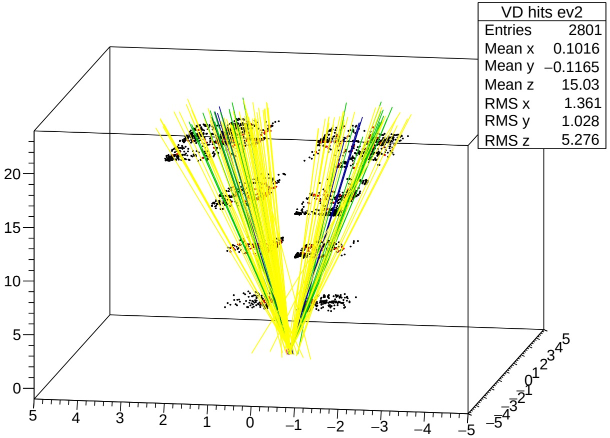
Data reconstruction

- **Geometry tuning**
- Track finding
- Primary Vertex Reconstruction
- SAVD-TPC track matching
- analysis with full particles information

SAVD geometry tuning

Geometry tuning:

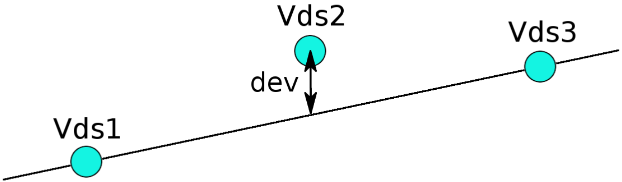
- finding the corrections for the sensor positions
- using tracks reconstructed without magnetic field



Deviation variable definition

In order to define the collinearity of three hits, the variable “dev” was introduced:

$$\mathrm{dev}_x = \frac{x_1 + x_3}{2} - x_2$$
$$\mathrm{dev}_y = \frac{y_1 + y_3}{2} - y_2$$

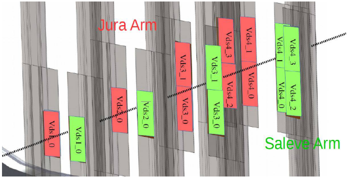


Generally, the problem is to minimise the sum of deviations – minimisation of function of 48 parameters (8 sensors; each has 6 degrees of freedom).

Geometry tuning – algorithm

VD Tracks Names:

- down1: Vds1_0, Vds2_0, Vds3_0, Vds4_0;
- down2: Vds1_0, Vds2_0, Vds3_0, Vds4_2;
- up1: Vds1_0, Vds2_0, Vds3_1, Vds4_1;
- up2: Vds1_0, Vds2_0, Vds3_1, Vds4_3;

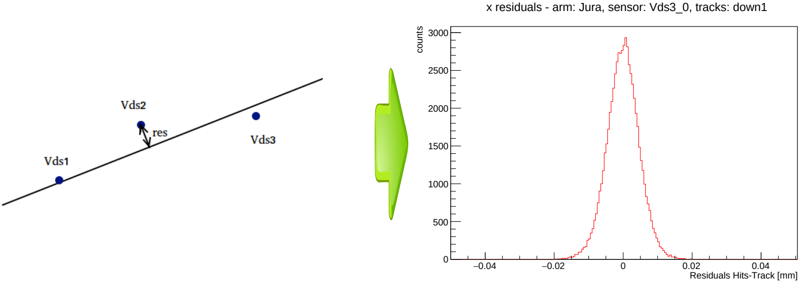


- fix the position of first sensor (reference);
- loop over down1 track candidates, calculate the sum of "dev" values, minimise the obtained sum using the MINUIT package by changing the offsets and rotation corrections of included sensors;
- fix the position of Vds2_0, Vds3_0, Vds4_0 sensors;
- do the same minimisation for up1 track candidates and fix the position of Vds3_1, Vds4_1;
- do the same minimisation for up2 and down2 track candidates and fix the position of Vds4_3, Vds4_2;

Final tuning

Final tuning:

- all sensors in parallel
- minimisation of standart deviation and mean values of residuals distributions

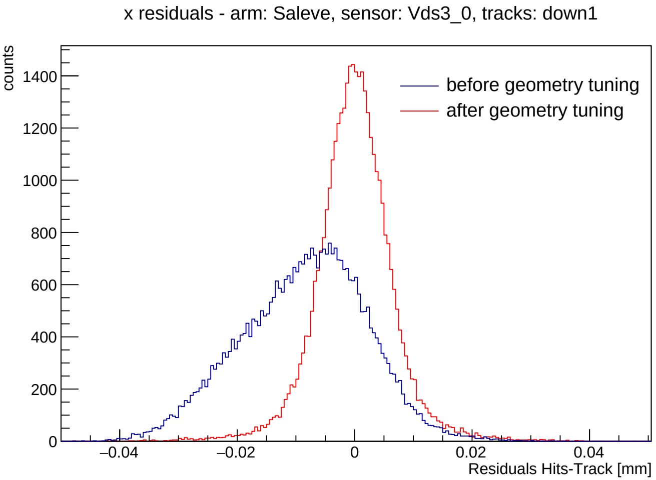


The improvement factor was calculated from the following formula:

$$\text{improvement} = \frac{\sigma_{oldGeometry} - \sigma_{newGeometry}}{\sigma_{oldGeometry}} \cdot 100\%$$

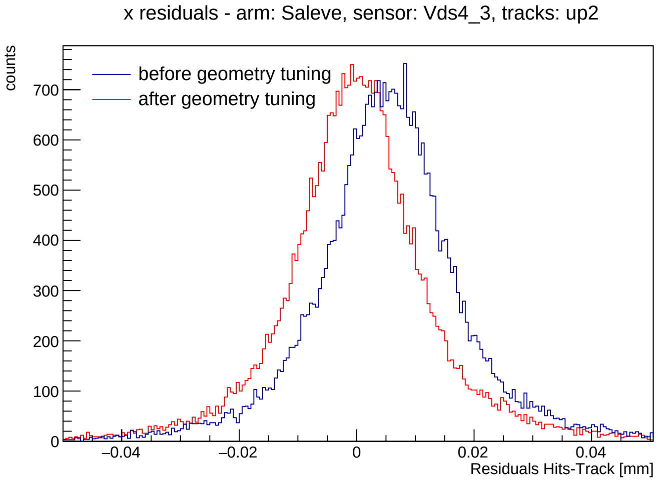
Saleve - biggest improvement

Improvement: 46.9 %



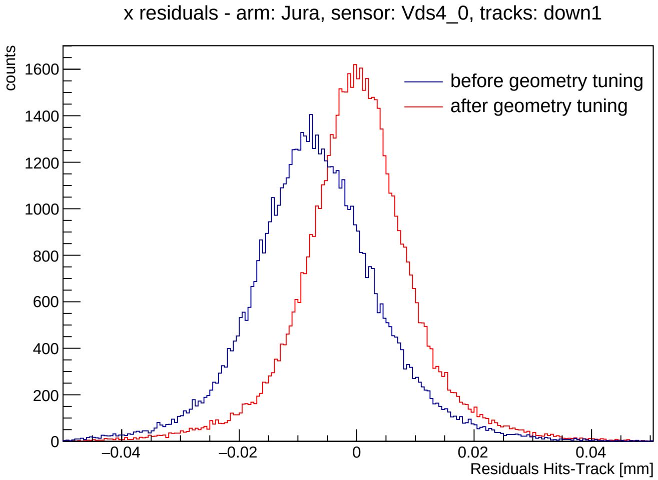
Saleve - smallest improvement

Improvement: 2.7 %



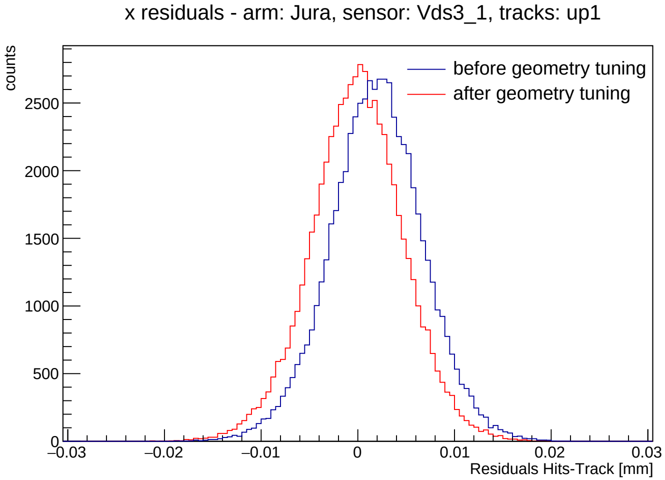
Jura - biggest improvement

Improvement: 16.5 %



Jura - smallest improvement

Improvement: 0.7 %

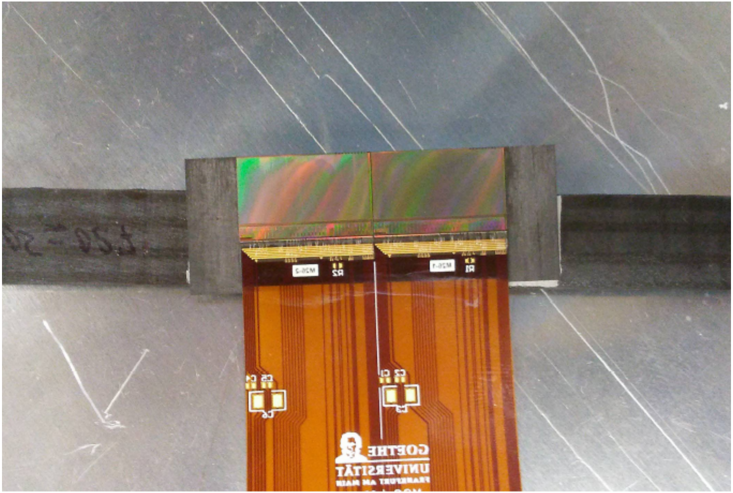


Example results:

Example results (data taken in December 2016):
Jura: sensor from 4th station:

- rotations:
  - rotX = -0.01 (0.6°)
  - rotY = 0.01 (0.6°)
  - rotZ = -0.049 (2.8°)
- offsets from nominal geometry:
  - offsetX = 2.1 mm
  - offsetY = 1.1 mm
  - offsetZ = 0.5 mm

Dismounted sensor in July 2017



Always read instructions!!!

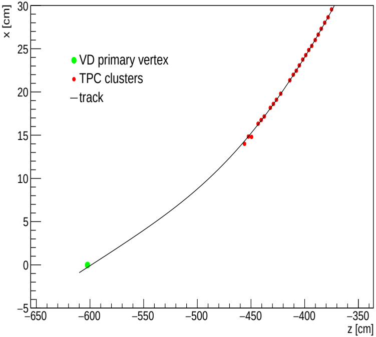
Data reconstruction

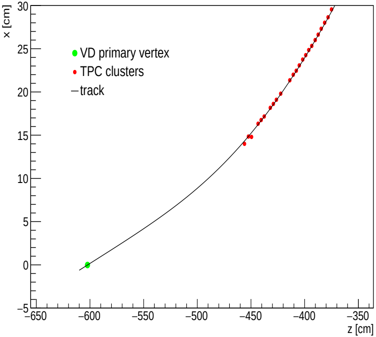
- Geometry tuning
- Track finding
- Primary Vertex Reconstruction
- **SAVD-TPC track matching**
- analysis with full particles information

Algorithm of matching: Primary Tracks

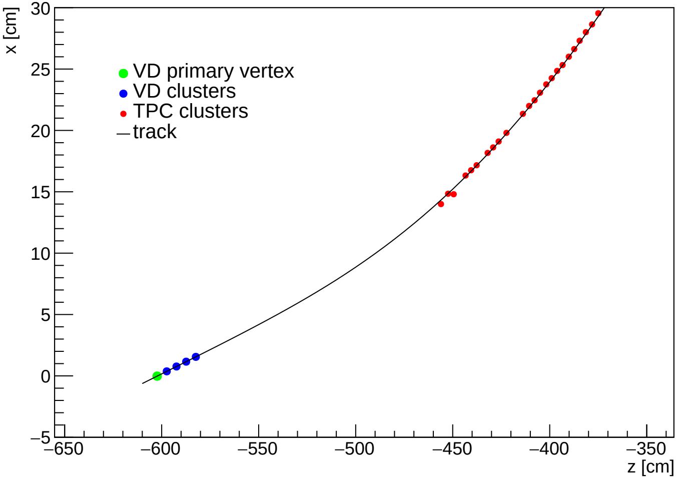
1st step: Refit track to VD primary vertex

For refitting **Kalman filter** existing in SHINE is used

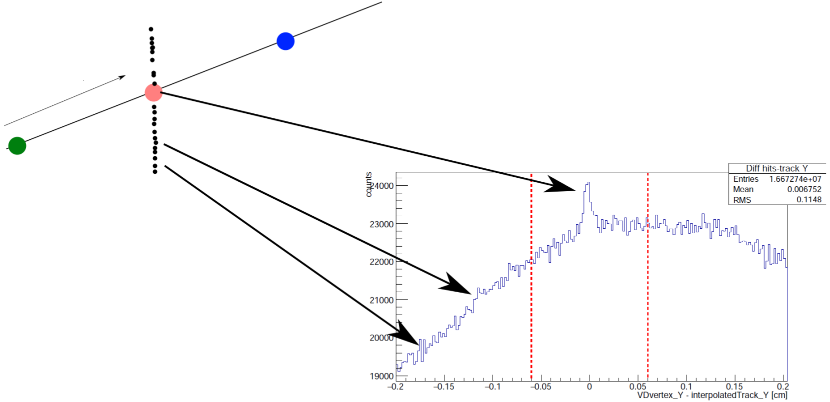




2nd step: Interpolate refitted track to VD stations and collect clusters

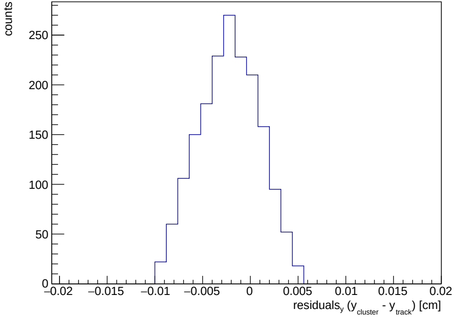


How to collect clusters?



Residuals cut

- distributions of residuals between clusters and refitted tracks are fitted with gaussian (σ)
- cluster is accepted as matched if the distance from track is smaller than 2σ



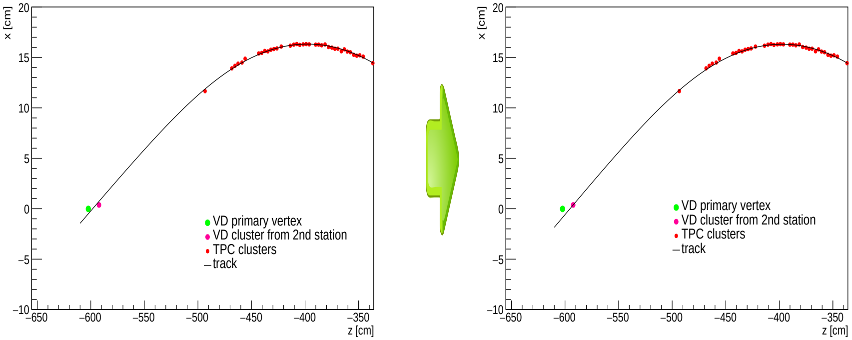
y-residuals between clusters from first station and refitted track: plot was created with 3σ cut, but to make sure that only primary tracks are matched, in the analysis 2σ cut is used.

Track is accepted as primary track if at least **one VD cluster** is matched (as first approach)

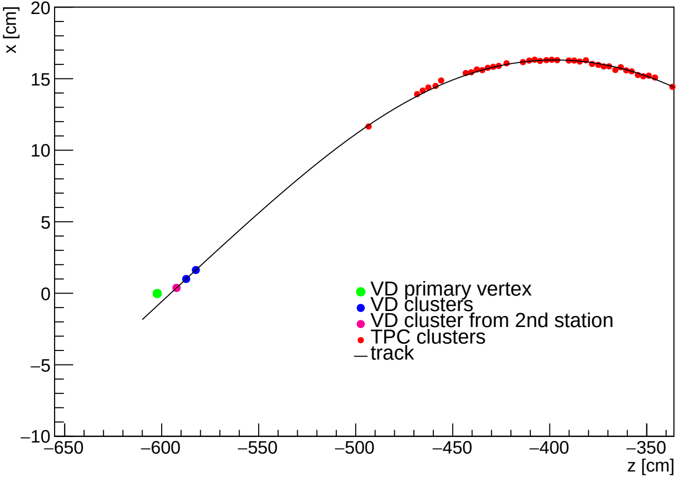
Algorithm of matching: Secondary tracks

3rd step: Refit track to VD cluster from second station

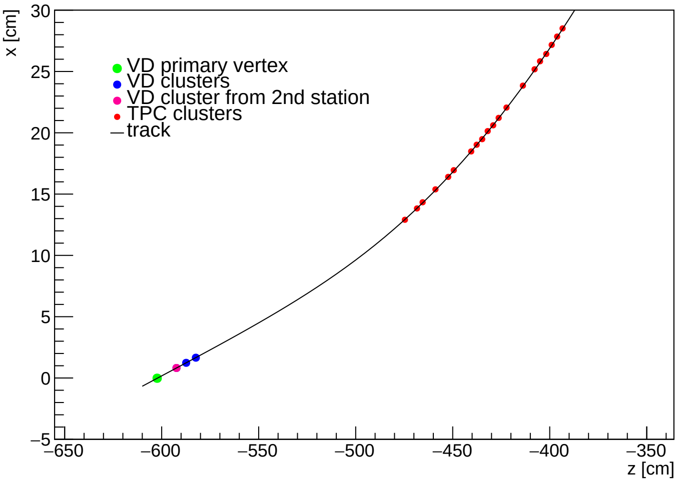
Every track is combined with all VD clusters from second station.



4th step: Interpolate refitted track to VD stations and collect clusters

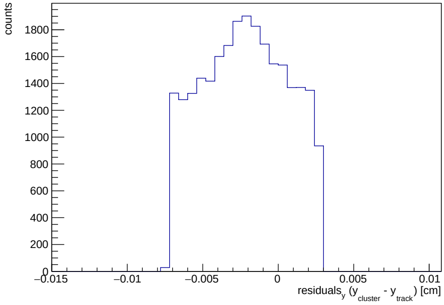


4th step: Interpolate refitted track to VD stations and collect clusters



Residuals cut

- the σ cuts values are taken from primary tracks analysis
- cluster is accepted as matched if the distance from track is smaller than 3σ



y-residuals between clusters from first station and refitted track: background from fake tracks is visible, but it is better to have more fake tracks than lose efficiency.

Track is accepted as secondary track if at least **three VD clusters** are matched (one refitted from second station + 2 clusters from other stations)